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Metal Particulate Emissions from Stationary Sources. Volume 2 Characterization of Collection Filters

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The literature on filtration theory and past experimental work was reviewed and critiqued with regard to the needs of the EPA relative to stationary source sampling. A laboratory evaluation of aerosol collection efficiency and flow resistance of filters potentially useful in EPA sampling programs was designed with respect to several variables, including particle size (0.05, ~ 0.1 and 0.5 μm MMD); gas velocity (4, 12, 30, 83 and 126 cm/sec); and aerosol composition and density (g/cm^2) - DOP (1.0), Na Cl (2.17), Be $SO_4 \cdot 2\ H_2O$ (2.36), Pb $(NO_3)_2$ (4.53), and Cd I (5.67). Filter collection efficiencies were measured for the various evaluation parameters with a DOP penetrometer or sodium flame photometer. With two exceptions, collection efficiencies of greater than 99 percent were obtained for all filters and test conditions. The exceptions, tested with 0.3 μm MMD Na Cl aerosol, were Millipore Mitex and Whatman 41 filters, with collection efficiencies of 75 and 50 percent, respectively. The other membrane filters (Millipore AA and Fluoropore) exhibited high flow resistance at 30 and 83 cm/sec and could not be tested at higher flow rates.

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by

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ABSTRACT

Promulgated standards of performance for several new stationary sources include regulations for permissible levels of mass emissions. Many of these sources can contain trace levels of potentially hazardous metal species which, when present as particulate, are submicron. Such particulate can easily penetrate to the lower airways, resulting in a hazard to health. As a result, a program was undertaken to develop reliable methods for measuring trace elements in emission streams. This report describes the measurement of filter collection efficiency for submicron, hazardous metal particulate. The literature on filtration theory and past experimental work was reviewed and critiqued with regard to the needs of the EPA relative to stationary source sampling. A laboratory evaluation of aerosol collection efficiency and flow resistance of filters potentially useful in EPA sampling programs was designed with respect to several variables, including particle size (0.05, ∿ 0.1 and 0.5 μm MMD); gas velocity (4, 12, 30, 83 and 126 cm/sec);and aerosol composition and density (g/cm^2) - DOP (1.0), Na Cl (2.17), Be $SO_4 \cdot 2 H_2O$ (2.36), Pb $(NO_3)_2$ (4.53), and Cd I (5.67). Other parameters, such as evaluation temperature, electrostatic charge, aerosol concentration, filter loading, and gas composition, pressure and relative humidity, were held constant or were not considered. Evaluation filters included glass (Gelman Spectro Grade without silicone treatment, MSA 1106 BH, and Arthur D. Little/Balston Microquartz), organic membrane (Millipore AA - mixed cellulose esters, Millipore Fluoropore - Teflon and polypropylene, and Millipore Mitex - Teflon) and paper (Whatman 41). Test aerosols were collected by a thermal precipitator for sizing by electron microscopy. Most of the aerosols exhibited log normal frequency distributions, with geometric standard deviations ranging from 1.3 to 1.9. Filter collection efficiencies were measured for the various evaluation parameters with a DOP penetrometer or sodium flame photometer. With two exceptions, collection efficiencies of greater than 99 percent were obtained for all filters and test conditions. The exceptions, tested with 0.3 μm MMD Na Cl aerosol, were Millipore Mitex and Whatman 41 filters, with collection efficiencies of 75 and 50 percent, respectively. The other membrane filters (Millipore AA and Fluoropore) exhibited high flow resistance at 30 and 83 cm/sec and could not be tested at higher flow rates. In general, the filter media tested (excluding Mitex and Whatman 41) have adequate collection efficiencies for the collection of particles containing hazardous metals. Other factors, however, such as thermal stability and background levels of trace elements, may influence filter selection for a particular stack sampling application.

This report was submitted in fulfillment of Contract No. 68-03-0286 by Arthur D. Little, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period June 25, 1973 to February 25, 1977, and work was completed as of November 1, 1977.

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SECTION 1

INTRODUCTION

Standards of performance for several new stationary source categories have been promulgated by the Environmental Protection Agency. Regulations for particulate emissions are generally related to permissible levels of mass emissions which are determined by sample collection and gravimetric analysis. Several recent technical publications have indicated that many of the potentially hazardous metal species present at trace levels in emission streams are largely submicron in particle size. Because of their size, collection by present control systems is not very efficient, leading to a potential for significant emissions to the atmosphere. Such submicron-sized particulate can be a hazard to health, penetrating to the lower airways of the lung when inspired. As a result, there is the need to develop reliable methods for measuring trace elements in emission streams.

Hazardous air pollutants are defined as those which "may cause or contribute to an increase in mortality or an increase in serious irreversible or incapacitating reversible illness". At present, asbestos, beryllium and mercury have been declared hazardous. Emission standards and sample collection and analysis methods have been promulgated for beryllium and mercury emissions from several source categories. Other trace metals, including lead, cadmium, vanadium, manganese, cobalt, nickel, arsenic and selenium have been implicated as possibly leading to health impairment. Before standards can be set, it is necessary to develop suitable sampling and analysis procedures for each of these metals.

Additionally, the typical size of metal particulate for the elements of concern is reported to be in the range 0.1 - 1 μm, a size which corresponds to the poorest collection efficiency for stack sampling filters and for pollution control devices. Further information about the properties of high temperature particulate collection filters is therefore necessary to determine any limitations with respect to sampling and analysis methods.

To address these needs, an experimental program was developed and conducted in two concurrent phases. The results of this work are described in separate reports. Volume I describes the development of standard sample collection and analysis methods for nine metals and an evaluation of the promulgated test methods 101 and 104 for mercury and beryllium, respectively. Volume II presents a review of stack sampling filter requirements and provides characterization data for the most promising filter candidates.

SECTION 2

CONCLUSIONS

Several types of filters suitable for stack sampling were evaluated for aerosol collection efficiency and flow resistance. From this work, the following conclusions can be drawn:

- Filter media including MSA 1106 BH, Gelman Spectro Grade (without silicone), Arthur D. Little/Balston Microquartz, Millipore AA and Millipore Fluoropore FA have collection efficiencies greater than 99 percent for the following ranges of conditions.
  - Aerosols: 0.3 μm Dioctyl Phthalate (DOP) and NaCl, $BeSO_4 \cdot 4H_2O$, CdI_2 and $Pb(NO_3)_2$.
  - Sizes: 0.03 to 1.3 μm MMD with geometric standard deviations of 1.4 to 1.9.
  - Flow rate: 12 to 125 cm/sec.
- The membrane-type filters, Millipore AA and Fluoropore FA, exhibited high flow resistance at 30 and 83 cm/sec, respectively (i.e., 78 and 114 mm Hg) and could not be tested at higher flows.
- Within the limits of measurement sensitivity, there was no difference in efficiency for variations in aerosol mass (1.0 to 5.7 g/cm^3) or size (0.03 to 1.3 μm MMD).
- Millipore Mitex membrane and Whatman 41 cellulose fiber filters with efficiencies of 75 and 50 percent (for 0.03 μm NaCl) are unsuitable for stack sampling applications.

In general, it is concluded that the filter media tested (excepting Millipore Mitex and Whatman 41) have adequate collection efficiencies for the collection of particles containing hazardous metals. Other factors (such as thermal stability and background levels of trace elements) may influence filter selection for a particular stack sampling application.

SECTION 3

RECOMMENDATIONS

Areas in which further work is recommended include the following:

- Measure filter efficiencies for a selected particulate challenge sample as a function of prior filter loading, aerosol charge and gas humidity.

- Measure the utility of organic membrane filters at temperatures of 120-150°C for times up to two hours, in simulation of stationary source sampling. For example, the test filter could be backed up by a quartz filter maintained at ambient temperature; nitric acid digestion and atomic absorption spectrophotometric analysis of the metal component of the particulate challenge for the two filters would provide a measure of efficiency.

- Carry out efficiency measurements for trace levels of hazardous metal particulate (10-100 $\mu g/m^3$) in the presence of typical levels of particulate emissions from stationary sources (20-200 mg/m^3) to determine if there is a preferential penetration of hazardous metal particulate during particulate sampling.

- Screen candidate filters for their suitability in carrying out trace hazardous metals analysis by various analytical methods, including x-ray fluorescent analysis and atomic absorption spectrophotometry.

SECTION 4

PROGRAM SCOPE

The requested program to develop a filter efficiency testing program included the following specific elements:

a) Compile a brief on filtration theory and past experimental work relevant to EPA requirements and write a critique on this work from the viewpoint of the EPA application need. This approach will differentiate EPA needs from the original purpose of the experimental work.

b) Design a test program based on the above critique and history which will provide the data to support EPA needs in the area of particulate sampling and analysis. Upon completion of the design, the contractor shall provide an Interim Report.

c) Execute, upon the approval of the Project Officer, a laboratory program based on the above design. Test filters currently used or potentially useful in EPA sampling programs. Testing shall include standard aerosol materials such as DOP, sodium chloride or latex spheres and aerosol materials of hazardous metal emissions. Operating parameters (velocity, geometrical arrangement, temperature, particle shape, 2.0 μm size particles, face velocity of 100 cm/sec, both Millipore and Fluoropore membrane filters) shall be representative of those encountered during stationary source sampling. Aerosols tested shall include beryllium and at least two other metals from the hazardous substances list.

d) The contractor shall provide to the EPA project officer at least two filters on which samples have been collected from a stationary source expected to contain trace levels of hazardous metals. The samples will be used by EPA and not for the analytical data required for the execution of of Tasks a) through c) above.

    1) The samples shall be collected on Millipore or Fluoropore filters.

    2) A blank from the same filter batch used for each sample collected shall be provided.

    3) The mass deposited on each filter and the sampling conditions at which the sample was collected shall be provided.

The ultimate purpose of this study was to identify filter media having acceptable properties for the efficient collection of particles containing hazardous metals for the range of conditions encountered in stack sampling. A collection efficiency of at least 99 percent for the hazardous metal containing particulate was deemed adequate for this purpose.

SECTION 5

FILTRATION THEORY AND APPLICATION PARAMETERS

FILTRATION THEORY

The simplest theoretical approach to describing the action of depth fiber filters for the collection of particulate matter is called the method of isolated fibers[1]. The principle of this method is as follows: the velocity field around an isolated straight cylindrical fiber (positioned normal to flow) is used to calculate the deposition efficiency of particles on the fiber due to the various mechanisms of deposition, which will be described below; then the combined effect of all fibers is used to determine the overall efficiency of the filter mat. Aerosol particles are assumed to be spherical in the isolated fiber approach.

Assuming that all collisions between particles and fibers result in permanent removal of the particles from the air stream, we can define the single fiber efficiency, E_s, as the fraction of particles approaching a fiber in the projected area stream that are ultimately deposited on the fiber (see Figure 1). The overall filter efficiency, E_t, of a fiber mat of unit area and thickness, t, in terms of E_s is given by Equation (1):

$$E_t = 1 - \exp\left[\frac{-4t\ \alpha\ E_s}{\pi\ d_f\ (1-\alpha)}\right] \qquad (1)$$

The term α is the ratio of fiber volume to total filter volume and d_f is diameter of the fiber cross-section.

Particles may be collected on a fiber through the action of the following mechanisms: interception, impaction, diffusion, sedimentation, and electrostatic effects. These mechanisms are briefly described below.

Interception is the capture of a particle having a finite size but negligible inertia because the streamline on which the particle is traveling happens to pass less than a particle radius, $d_p/2$, away from the fiber, as shown in Figure 2. Collection by this mechanism increases with the interception parameter, $J = d_p/d_f$, and with the Reynolds number. The latter is a result of the squeezing of streamlines near the fiber at higher Reynolds numbers.

Collection by impaction results when a particle, because of its inertia, is unable to adjust quickly enough to the abruptly changing streamlines in the vicinity of a fiber and crosses streamlines to hit the fiber, as shown in Figure 3. The key parameter for this mechanism is the impaction parameter, the ratio of the particle stop distance to the fiber diameter. Particle stop distance, a measure of inertia, is the distance the particle would continue to travel if the surrounding air were instantly made motionless. The impaction parameter, ψ, is given by:

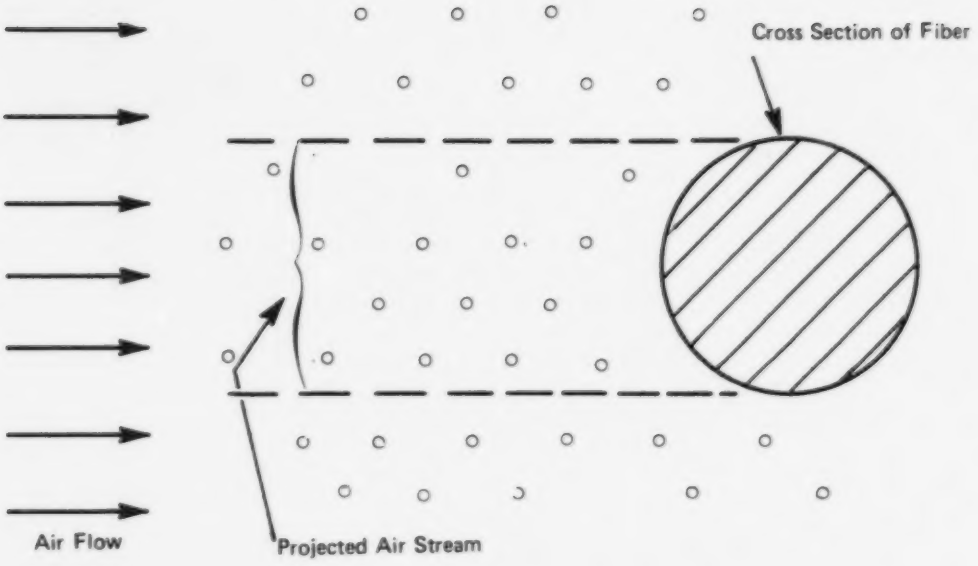


Figure 1. Single fiber collection efficiency.

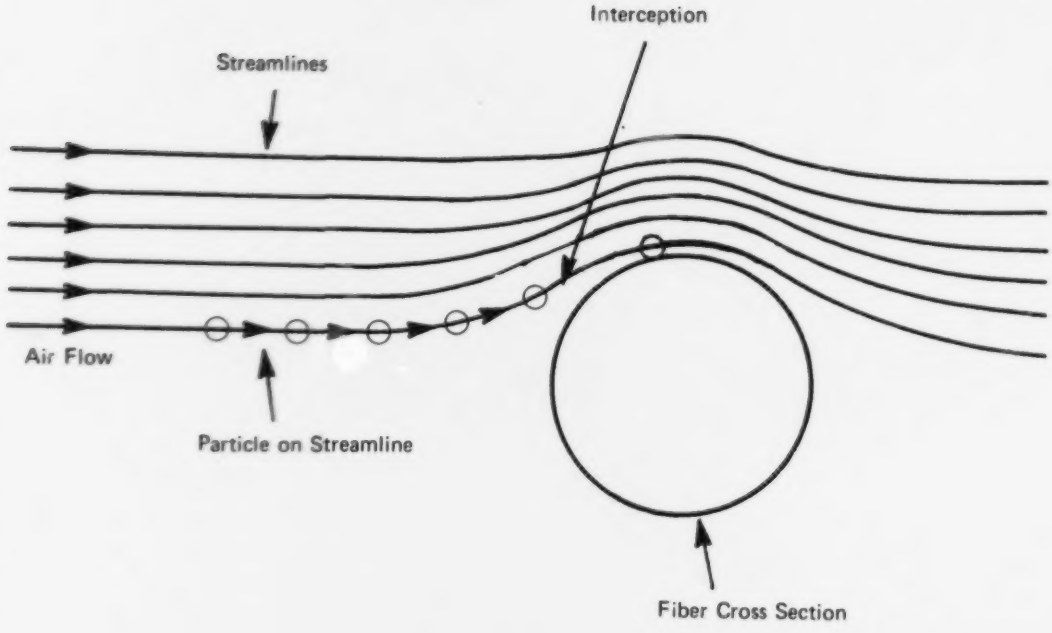


Figure 2. Particle collection by interception.

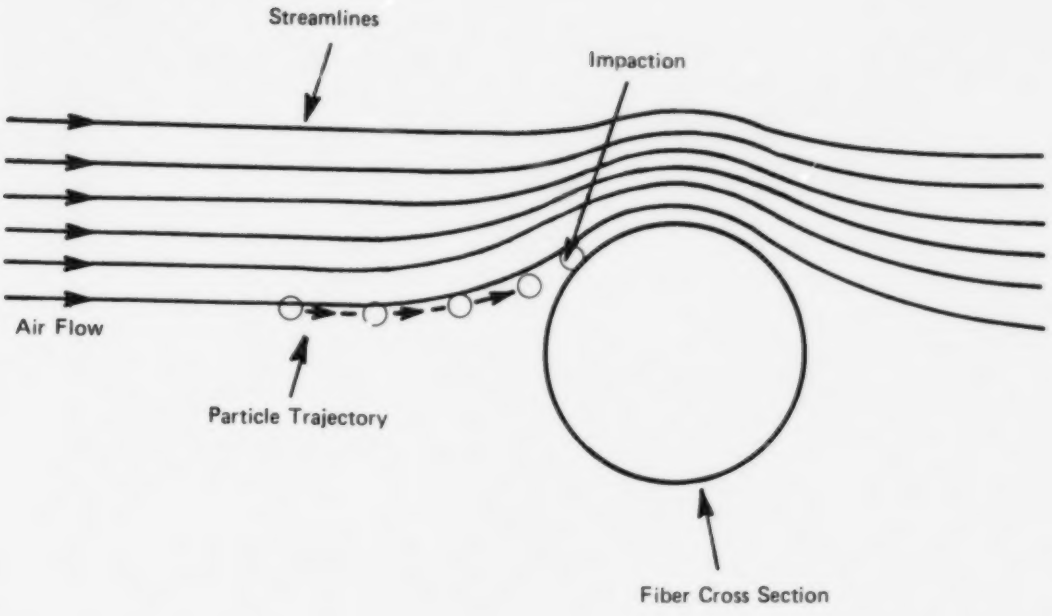


Figure 3. Particle collection by impaction.

$$\psi = \frac{\rho_p d_p^2 D_c U_o}{18 \eta d_f} \qquad (2)$$

where ρ_p is the particle density; U_o, the undisturbed gas velocity; η, the gas viscosity, and D_c, the slip correction. Efficiency is related to ψ in a complex way. Collection efficiency by impaction increases with increasing ψ. This could result from: 1) greater particle inertia, i.e., increases in d_p or ρ_p, or, 2) increased abruptness of change in the flow streamlines due to increased U_o or decreased d_f.

Diffusion is most important for small particles for which the magnitude of the Brownian motion is sufficient to enhance the probability of the particle hitting a fiber while passing by on a non-intercepting streamline (see Figure 4). The single fiber efficiency due to Brownian motion is usually expressed in terms of the Péclet number, a dimensionless parameter, defined as:

$$Pé = \frac{d_f U_o}{D} \qquad (3)$$

The diffusion coefficient, D, is a measure of the intensity of Brownian motion and varies inversely with particle diameter. Efficiency increases with decreasing Péclet number (or in other words with decreasing particle size, and/or with decreasing fiber diameter).

Sedimentation or settling due to the influence of gravity is of little significance under most filter sampling conditions, as the effect is overshadowed by a much higher impaction efficiency for those particles that are large enough to have a significant settling velocity.

Electrostatic deposition can be extremely important but is difficult to quantify because it requires knowledge of the charge distribution on both the particle and on the fiber. Under most conditions increasing charge on either particle or fiber will lead to increased deposition efficiency.

The overall single fiber efficiency cannot be obtained by simply adding the efficiency of each mechanism because different mechanisms may be competing for the same particle. Usually, one assumes that one mechanism dominates and the overall efficiency can be attributed to that mechanism. It is common to treat the closely related mechanisms of impaction and interception together. As a first approximation, impaction and diffusion are mutually exclusive, since they are effective in different particle size ranges, and can be combined by arithmetic sum. Application of these simple ideas to filters is further complicated because there is a range of fiber diameters present. However, based on the preceding discussion, some general observations can be made.

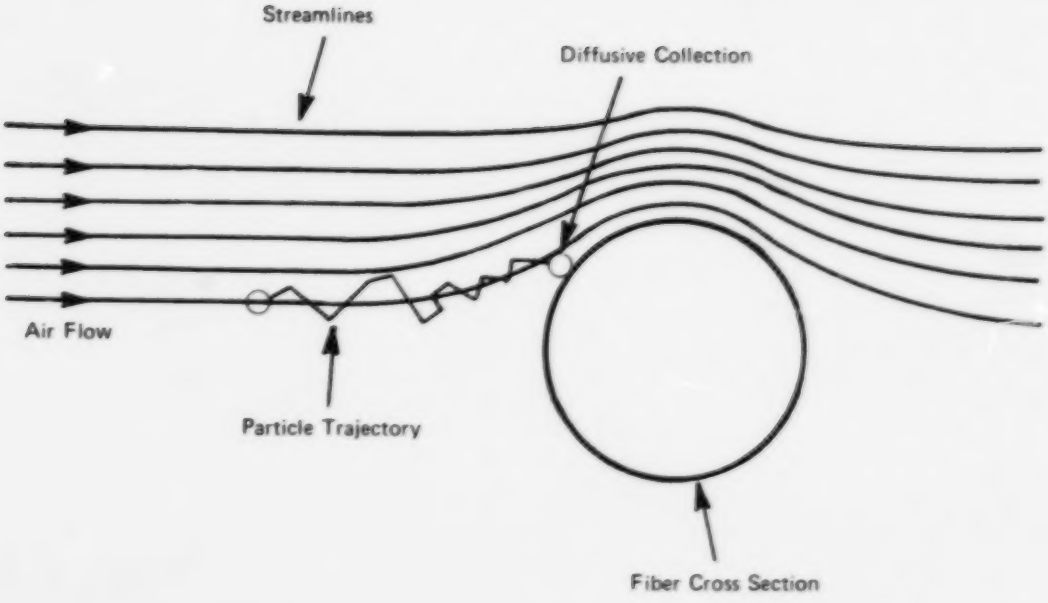


Figure 4. Particle collection by diffusion.

- For constant flow velocity there is a particle size for which the efficiency is minimum (see Figure 5). This is due to the effectiveness of the impaction mechanism decreasing with decreasing particle size, whereas the diffusion mechanism becomes more effective as particle size decreases. For conditions encountered in high efficiency filters, the size for minimum efficiency is in the submicron range.

- Similar reasoning leads to the prediction of a velocity of minimum efficiency for a given particle size.

- In general, collection efficiency increases with decreasing fiber diameter.

- Efficiency increases with decreasing porosity (increasing α).

In practice, collisions between particles and fibers do not always result in the removal of particles. As particle size, density and stream velocity are increased, there is a greater tendency for the particles to bounce off. This generally results in a decrease in collection efficiency for particles larger than 5 μm.

The basic physical mechanisms for particle collection by fibrous filters described above also apply for depth membrane filters. In addition, collection by sieving (in which particles must pass through a cake of dust collected on the surface of the filter) can be an important mechanism.

FILTER CANDIDATES

We proposed to limit this study to filters demonstrating at least 99 percent efficiency for the range of typical stack gas conditions. Candidate filter types include the following:

- High efficiency glass fiber mat

  This type of filter was developed for the Atomic Energy Commission for collecting radioactive particulates in ventilation systems. The glass fibers contain many impurities which interfere with analyses for trace metals. Nevertheless, this filter has been specified for use in the EPA stack sampling method for mercury* and is commonly used in many other stack sampling methods.

- High purity quartz fiber mat

  Arthur D. Little, Inc. developed a high purity quartz fiber filter under EPA Contract 68-02-0585 that is suitable for stack sampling applications up to 600°C. The high purity of the filter permits its use for many trace metals. Other quartz fiber filters are commercially available.

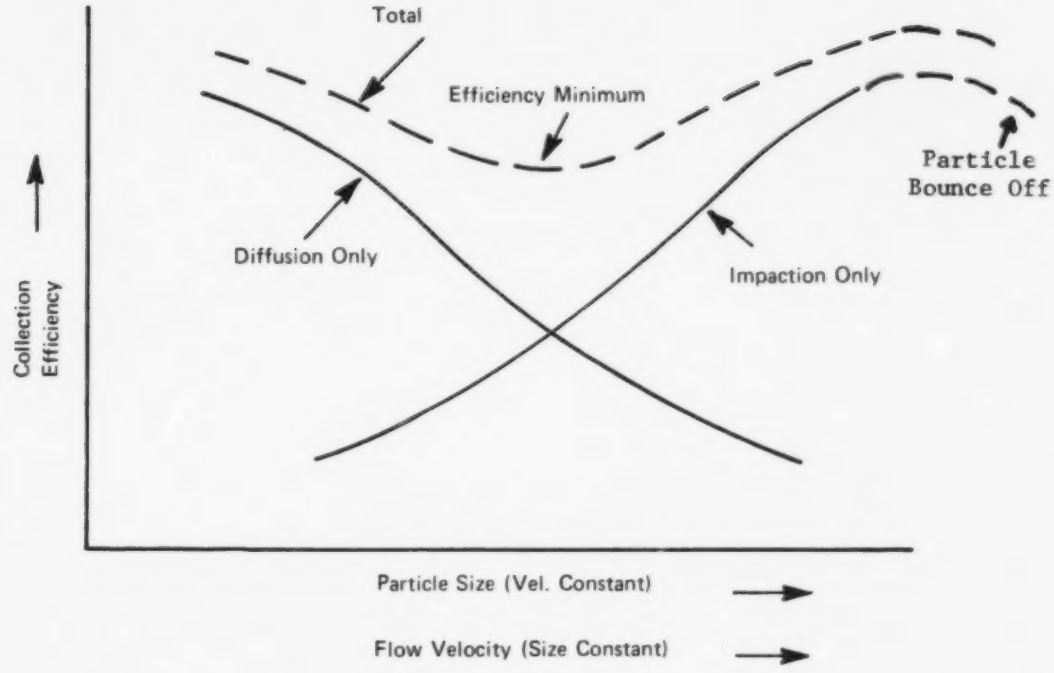


Figure 5. Effect of particle size and velocity on collection efficiency.

- Membrane filters

  Millipore AA (cellulose ester) has been specified for use in the EPA stack sampling method for beryllium.[2] It has a maximum pore size of 0.8 μm and is stable up to 120°C. It collects essentially all particles larger than 0.8 μm on the surface (by sieving) and many particles much smaller than 0.8 μm within the internal pore structure (by other filtration mechanisms). Other membrane filters, such as Fluoropore, Selas silver membranes, and Teflon membranes are also available.

- Whatman 41 paper

  This filter has been recommended for use as a backup filter to Millipore AA in the EPA beryllium sampling method. Its purity is high, but its efficiency is low and variable.[3,4]

APPLICATION PARAMETERS

Assuming that sampling filters will be used under a wide range of stack conditions and that some conditions such as particle size are not usually known, data on filters with widely varying efficiencies are not very useful. Sampling filters with more nearly constant efficiencies over a wide range of stack conditions are needed. The efficiency need not be high, but a constant high efficiency (e.g., over 99%) is both more useful and achievable.

As described in Section A, aerosol filters collect particles primarily by sieving, diffusion, direct interception, and inertial impaction. Electrostatic collection is also important in some filters. It should be noted, however, that filtration theory is more useful as a guide to design of filters and interpretation of experimental findings than for predicting filtration performance over wide ranges of operating conditions. The efficiency of a filter is highly dependent on both filter structure and filtration conditions. In general, efficiency increases with decreasing fiber diameter or pore size of the filter. Parameters that can have a significant influence on collection efficiency are discussed in the following sections.

Particle Size

Particle size is probably the most important, yet most misinterpreted, variable affecting filter efficiency. Two common misinterpretations are that membrane filters do not collect particles smaller than the rated pore size, and that high-efficiency filters do not collect particles smaller than 0.3 μm diameter.

The misinterpretation about membrane filters results from their very important use in collecting particles larger than the rated pore size on the filter surface for microscopic examination. These large particles are collected by sieving. Smaller particles are collected within the filter structure, probably by diffusion and inertial impaction and possibly by electrostatics.

The misinterpretation about high-efficiency filters results from the common practice of stating but not explaining dioctyl phthalate (DOP) test results. The DOP test was designed during World War II to test high-efficiency gas mask filters against what was thought at that time to be the most penetrating particle size-0.3 μm (now believed to be between 0.1 and 0.3 μm diameter.[5-7] Particles smaller and larger than the most penetrating size are collected with greater efficiency, largely by diffusion and inertial impaction, respectively.

Gas Velocity

In general, particle collection efficiency decreases with increasing velocity at low velocities and then increases. This effect is due to decreased diffusion and increased inertial impaction. A notable exception is the Nuclepore membrane filter, which is a polycarbonate film containing straight-through holes. For this case, efficiency decreases continuously with increasing velocity.

As discussed in Section A, the efficiency of some filters for large particles decreases slightly at high velocities due to particle bounce. This effect has been observed primarily with particles over 5 μm in coarse filters at velocities over 100 cm/sec.[8,9] The effect should be minimal with respect to hazardous metal particulate which is generally expected to be submicron in size.

Particle Composition and Density

Except for the effect of particle density, filter efficiency should be independent of particle composition. Some unpublished stack sampling results, however, suggest that this may not be entirely true (e.g., beryllium has been reported to penetrate high-efficiency filters). Such apparent contradictions require careful consideration with respect to developing a filter testing program. Ideally, filters should be tested with the type of particles that are to be collected (in this case, hazardous metal pollutants).

A question can be raised as to the equivalence of initial efficiencies for solid and liquid aerosols of the same particle size, i.e., are liquid dioctyl phthalate (DOP) efficiency measurements equivalent to what would be expected for solid particles? Experimental data are limited but suggest that high efficiency filters have equal initial efficiencies for solid and liquid aerosols of the same particle size.[10-12]

The effect of particle density on filtration efficiency is of interest because most high-efficiency tests are performed with low-density (1 or 2 g/cc) DOP or sodium chloride particles, whereas stack emissions may contain particles of high density, such as PbO_2 (9 g/cc). This effect has been recognized in nuclear installations where even higher density particles, such as uranium dioxide (11 g/cc) must be collected. Filtration theory predicts that particle density should increase the efficiency of inertial impaction but not appreciably affect diffusional collection. This should be verified experimentally.

Temperature

In-stack sampling temperatures cover a wide range (from ambient to as high as 500°C). The effect of temperature over this range on filtration efficiency is therefore an important consideration. This effect has also been studied in nuclear installations where high-efficiency filters are used to prevent release of radioactivity in the event of an accident or fire. Dyment[13] discusses this subject, as follows:

"At elevated temperature, gas viscosity will increase and therefore increased pressure drops will be obtained for the laminar flow conditions which prevail in high-efficiency paper media under normal ambient conditions."

"The effect of temperature on fiber filtration mechanisms has been summarized by Thring and Strauss[14] in terms of inertial, interception, and diffusional collection. Because of the way in which the three mechanisms vary with conditions (i.e., fiber and particle sizes, fluid velocity), a general rule cannot be formulated for the effects of temperature on filtration performance. When the predominant mechanism is known, however, the effects can be predicted qualitatively. Inertial and interception efficiency are reduced by increased temperature. For the larger particles for which inertial impaction is more important, changes in particle-fiber adhesion at high temperature may exaggerate or modify this effect. The diffusion mechanism is of increasing importance as particle size diminishes below one micron. For diffusion the effect of temperature rise is to increase the fiber collection efficiency particularly for submicron particles."

Pich and Binek[15] made a theoretical analysis of the effect of temperature on the efficiency of mechanical filtration by diffusion, interception and inertia in fibrous filters. They derived an expression for the temperature at which filtration efficiency would be minimal. This temperature depended on the size and density of the particles and the air velocity.

Dyment[13] also reported the results of some glass fiber filter tests with sodium chloride aerosol at temperatures up to 500°C. He found that glass paper shrinks at these temperatures, so he preheated the samples to avoid cracking failure. His data, while extremely limited, suggest that increasing temperatures to 400°C slightly decreased filter efficiency. His conclusions were as follows:

"In practice, the effect of temperature and pressure on filtration mechanism and performance has not been found a determining factor in the application of high-efficiency filters. The main problems are the physical and chemical effects of a high temperature environment on the materials of construction of the filter, which are manifested by reduced mechanical strength and resilience or loss of adhesion, leading to mechanical leakage and loss in efficiency."

More recent high-temperature filter efficiency tests were reported by First.[16] Heat-shrunk quartz fiber filters were tested at temperatures up to 510°C with sodium chloride aerosols of 0.14 μm mass median diameter at velocities of 15 to 30 cm/sec. No effect of temperature on efficiency was found.

Electrostatic Charge

The effect of electrostatic charge on aerosol filtration efficiency has been the subject of much speculation and a few careful studies.[6,17-20] These studies indicate that filter efficiency increases under the following conditions:

1. Aerosol is charged and filter is uncharged.

2. Filter is charged and aerosol is uncharged.

3. Aerosol and filter are oppositely charged.

In general, improvements in efficiency increase from condition 1 to condition 3. The increases are greater with small particles at low velocities. On the basis of the assumption that filter efficiencies exceed 99% under all stack conditions, further filter testing under the above conditions is unnecessary.

However, the effect of electrostatic charge when the aerosol and filter are both positively or negatively charged should be investigated.

The latter condition could occur when sampling downstream of an electrostatic precipitator with a nonconductive filter holder, such as the glass apparatus in EPA Method 5 for particulate. An originally uncharged filter, if electrically insulated, will become charged by deposition of unipolarly charged aerosol. The accumulated filter charge might then reduce filter efficiency by repelling charged particles of the same polarity, as discussed by Pich.[21]

Aerosol Concentration and Filter Loading

Aerosol concentration has no theoretical effect on initial filtration efficiency, and no published reports of experimental studies of this variable have been found. However, filter loading generally causes an increase in filter efficiency. Two exceptions are as follows:

1. Liquid aerosols may reduce filter efficiency by altering the filter structure configuration. At loadings of 20 mg/cm^2, oil has been found to blow through high-efficiency glass fiber filters.[22]

2. Whatman 41 paper has been reported by Stafford and Ettinger[4] to decrease in efficiency at velocities over 50 cm/sec as the filter was loaded with polystyrene latex particles larger than 0.5 μm.

A solution to these exceptional loading situations is to use a filter sandwich consisting of two or more filters in each filter holder when sampling stacks and to analyze each filter separately. The additional filter(s) should be unnecessary in most cases, but is inexpensive insurance against possible overloading effects, as well as other problems, such as filter pinholes. Flow resistance will increase, but this should not be a serious problem in most sampling applications.

Gas Pressure and Composition

Filter efficiency generally increases somewhat at low pressure and decreases at high pressure.[13,23,24] However, because most stack sampling will be done at essentially 1 atmosphere, this effect will not be further discussed.

Gravimetric sampling filter measurements can be greatly affected by gas composition. For example, aerosol filters can gain weight by adsorption of water vapor or reaction with sulfur dioxide. This effect is beyond the scope of this study.

Gas Humidity

Increased gas humidity has been found to greatly increase the efficiency of collection of rather large particles (several μm diameter) by industrial filters.[8,25,26] This effect is attributed primarily to increased particle-to-filter adhesion (less particle bounce), and is not expected to be as large for smaller particles.

Humidity may alter electrostatic charges in membrane filters and thereby affect filtration efficiency. This effect was found to be negligible in Millipore AA filters,[27] but may be important for other types of membranes (such as Millipore Fluoropore).

SECTION 6

EXPERIMENTAL PROGRAM DESIGN

As discussed in Chapter 5, filter efficiency depends on both gas stream and aerosol particle properties. Parameters selected for evaluation and their levels are summarized in Table 1. The test aerosols were dioctyl phthalate (DOP), sodium chloride, beryllium sulfate, lead nitrate and cadmium iodide. DOP efficiencies were measured with 0.3 micrometer diameter particles at a face velocity of 5.3 cm/sec. Aerosol efficiencies were obtained for three different particle sizes for each of the four salts, and for five face velocities at each particle size. The face velocities varied from 4 to 125 cm/sec. Salt aerosol particle sizes (mass median diameter) ranged from about 0.03 to 1 micrometer. Air resistances were obtained simultaneously with the efficiencies.

The experimental program included measurements of the air resistance and particle collection efficiency of the filter media listed in Table 2. These particular media were selected for study in this program because of their potential usefulness in sampling hazardous metals.

Filter efficiencies were determined by passing test aerosols through samples of the filter media and measuring the aerosol concentration upstream and downstream of the filter. Efficiency was computed from the expression

$$E = \left(1 - \frac{C_d}{C_u}\right) \times 100 \quad \text{(percent)} \qquad (4)$$

where C_d and C_u are the downstream and upstream aerosol concentrations, respectively.

TABLE 1. RANGE OF SAMPLING VARIABLES INVESTIGATED

Variable	Level
Particle size	0.05, 0.1-0.2 and 0.5 μm MMD
Gas velocity	4, 12, 30, 83 and 126 cm/sec
Particle composition and density (g/cm^2)	DOP (1.0), NaCl (2.17), $BeSO_4 \cdot 4\ H_2O$ (2.36), $PbNO_3$ (4.53) and CdI (5.67)
Temperature	Pretreatment at 500°C (effects of high temperature exposure is measured rather than efficiency at high temperature)
Electrostatic charge	Not evaluated (aerosol charge neutralized)
Aerosol concentration and filter loading	Not to be varied. Convenient concentrations and clean filters will be used.
Gas pressure and composition	Not to be varied. Ambient air will be used.
Gas humidity	Not to be varied. Dry air will be used.

TABLE 2. FILTER MEDIA SELECTED FOR EVALUATION

Media	Composition	Type
Millipore AA	mixed cellulose ester	membrane (0.8 micron pore size)
Millipore Fluoropore FA	teflon-polypropylene	membrane (1 micron pore size)
Gelman Spectro Grade (without silicone treatment)	glass	fiber
Mine Safety Appliance Co. 1106BH	glass	fiber
Arthur D. Little/ Balston "Microquartz"*	quartz	fiber
Millipore Mitex	teflon	membrane (10 micron pore size)
Whatman 41	cellulose	fiber

*Samples from Trial II pilot scale production run (EPA Contract 68-02-0585)

SECTION 7

EXPERIMENTAL APPARATUS AND PROCEDURES

Two different types of filter penetrometers (apparatus for measuring filter efficiencies) were used in the program. DOP efficiencies were determined with an ADL Model 362 DOP penetrometer. The salt aerosol efficiencies were measured with an apparatus especially assembled for that purpose. These penetrometers and the procedures used with each are described below.

The ADL Model 362 DOP penetrometer (Figures 6 and 7) is similar in design to the Q127 penetrometer described in Military Standard 282.[28] It includes a thermal DOP generator, a visual "Owl" for particle size measurement, and an aerosol photometer for particle concentration measurement. The DOP aerosol generator is essentially a pot of DOP heated to about 170°C. Air heated to the same temperature is passed over the pool of DOP and picks up DOP vapor. Subsequently, the hot DOP-laden air is mixed with cool air to produce a supersaturated condition. DOP particles condense out of the supersaturated mixture. Particle size is controlled by the temperatures of these two air streams.

The visual "Owl" (Figure 8) is a device for measuring the polarization ratio of light scattered at right angles from a collimated beam of light by DOP aerosol confined in a cell. Particle size is obtained from the polarization ratio through computations made as a function of size from light scattering theory.[29] Aerosol concentration was measured with a forward light scattering photometer (Figure 9).

Evaluation filters tested with the Model 362 penetrometer are held in a chuck. An effective filtration area of 100 square centimeters is exposed to the aerosol. Gas flow through the filter is measured with a rotameter previously calibrated with a special orifice plate (calibrated by the National Bureau of Standards) designed to fit in the filter chuck. The procedures suggested in ASTM Method D 2986-71 were followed in making the DOP efficiency measurements.[30] All measurements were made at a face velocity of 5.3 cm/sec.

The salt aerosol efficiency measurements were made with the apparatus shown in Figures 10 and 11. Salt aerosol was generated by spray drying aqueous solutions of sodium chloride, beryllium sulfate, lead nitrate and cadmium iodide. Either an Environmental Research Corporation (ERC) Fluid Atomization Aerosol Generator or a DeVilbiss Model 35 ultrasonic nebulizer was used for aerosol generation. Aerosol concentrations were measured with a Frontier Enterprise Model FE260 Sodium Flame Photometer. Particle sizing was done by electron microscopy. The system is described in detail below.

Figure 11 shows the penetrometer as it was set up for using the ERC aerosol generator. The ERC generator includes a Collision nebulizer, which produces a mist of salt solution droplets, an impactor for removing the larger droplets, a mixer for introducing dry, filtered air into the gas stream to aid in the evaporation of the water from the mist droplets, and a two millicurie Krypton-85 aerosol charge neutralizer.

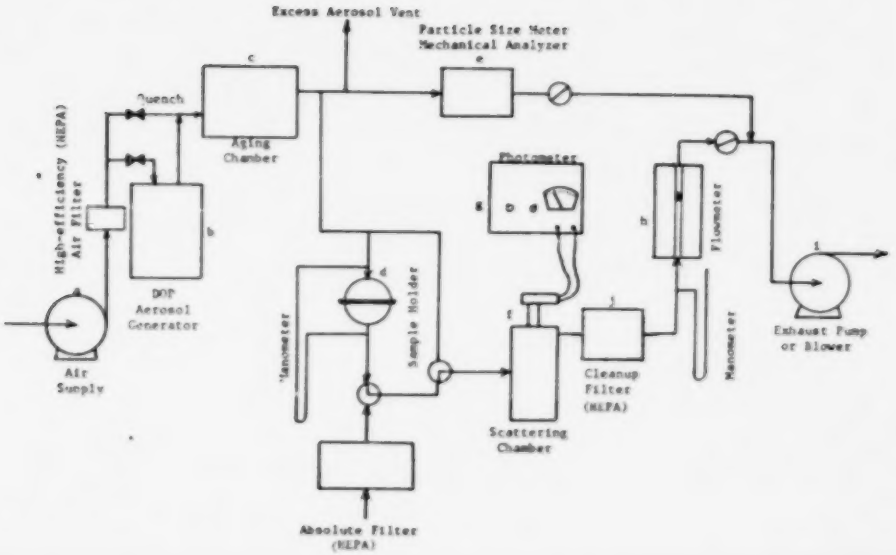


Figure 6. Simplified diagram showing relation of principal parts of DOP aerosol test apparatus.

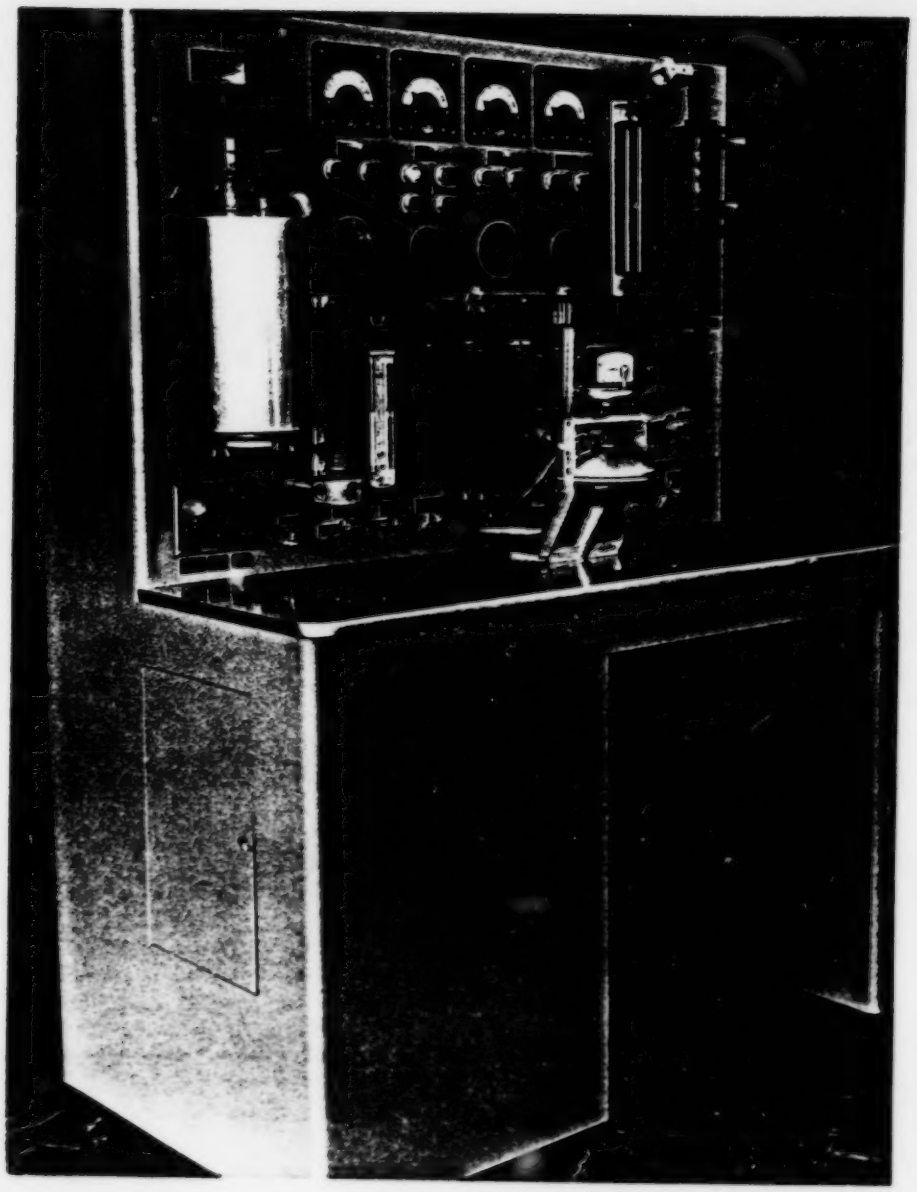
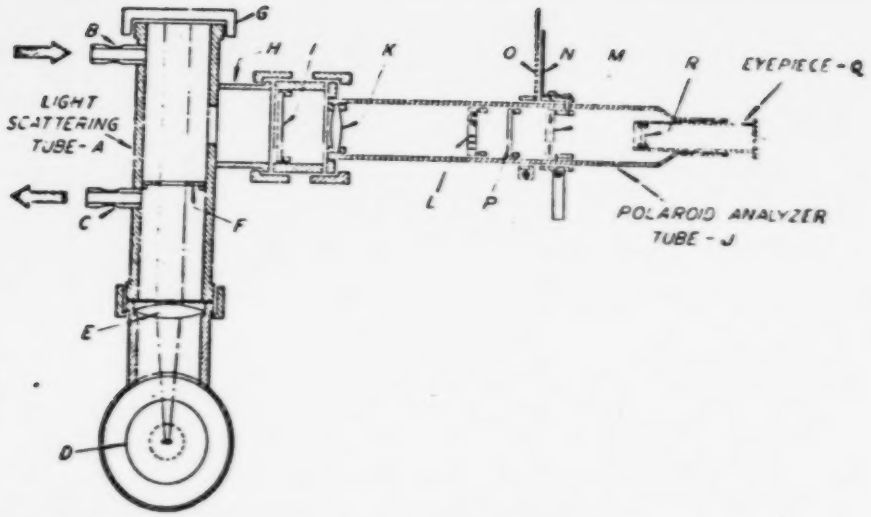


Figure 7. Arthur D. Little, Inc. Model 362 Dioctyl Phthalate (DOP) Penetrometer.



A—Smoke chamber and light-scattering tube
B—Smoke inlet port
C—Smoke outlet port
D—Light source
E—Lens to form parallel beam of light through smoke chamber
F—Baffle to reduce stray light scattered from walls of chamber
G—Velvet-lined cap on chamber
H—Side arm to light scattering tube
I—Smoke-retaining window
J—Polaroid analyzer tube
K—Light collecting lens
L—Bipartite disk (split field polaroid)
M—Polaroid disc mounted in movable collar
N—Indicator on polaroid holder to show angle of displacement from vertical axis
O—Degree scale for indicator (N)
P—Green filter for obtaining monochromatic light
Q—Adjustable eyepiece
R—Lens in eyepiece

Figure 8. "Owl" Particle Size Meter.

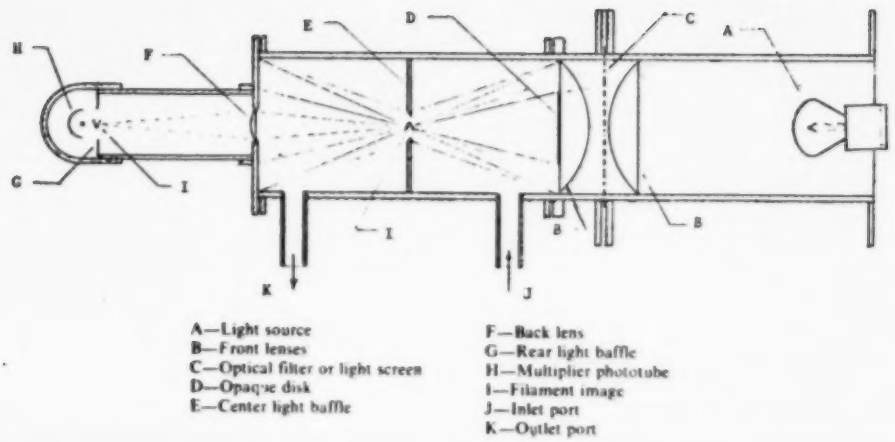


Figure 9. Light-Scattering Chamber -- schematic section showing optical system.

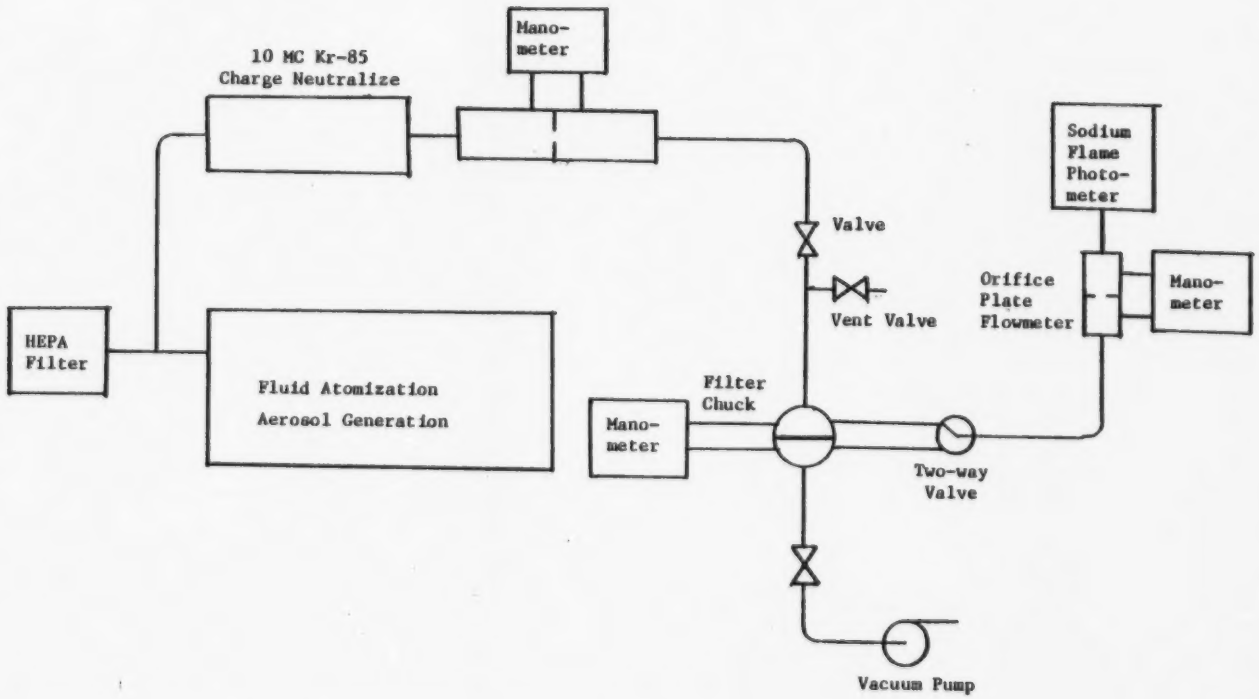


Figure 10. Schematic diagram of Salt Aerosol Penetrometer.

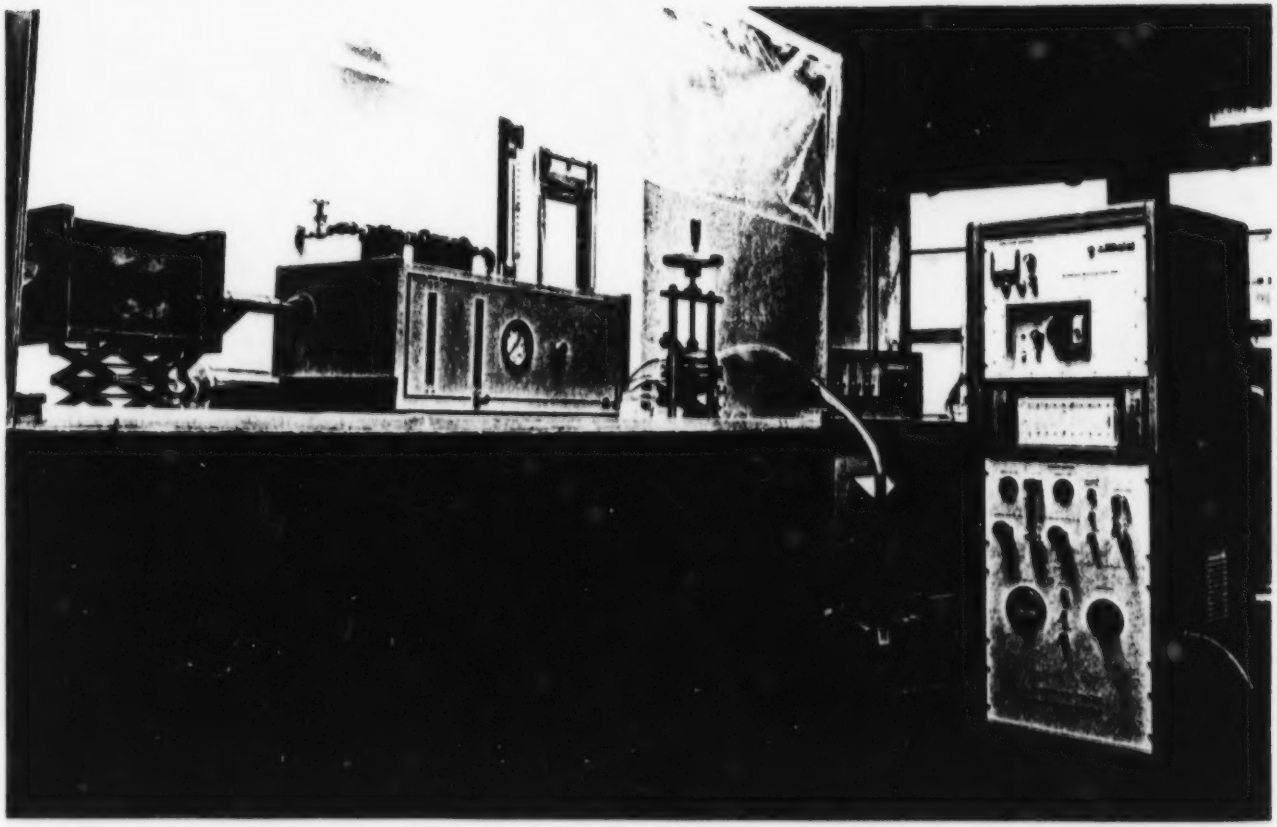


Figure 11. Photograph of Aerosol Generation and Filter Efficiency Measurement apparatus.

For producing salt aerosols with a size of 0.5 - 1.0 μm MMD, the Collision nebulizer was replaced by the DeVilbiss ultrasonic nebulizer. In this latter case, the impactor was removed; however, the other parts of the ERC generator were used.

Aerosol exiting from the ERC generator passes to a "Tee" section. Excess aerosol is vented through a HEPA filter. The remainder of the aerosol flows through a second Krypton-85 charge neutralizer (10 millicurie) and then through an orifice plate type flowmeter (3/8 inch diameter). The pressure drop across the flowmeter was measured with an inclined manometer.

The aerosol next passes through a valve and then to a specially constructed filter chuck. The chuck has ports for extracting samples for the flame photometer, attaching a manometer for measuring pressure drop across the filter, and collecting aerosol particle samples for size analysis. Filters are supported in the chuck on a 100 mesh stainless steel screen. The exposed filter area is either 100, 14.2, or 9.4 cm^2. Combinations of these three areas plus two aerosol volume flow rates, were used to obtain five different filter face velocities corresponding to 4, 12, 28, 83, and 126 cm/sec.

Aerosol was drawn through the evaluation filter by a vacuum pump. The aerosol generator was set up to produce a constant volume of aerosol. Aerosol flow through the filter was controlled with a regulating valve downstream of the filter chuck. As mentioned above, excess aerosol was vented through a HEPA filter.

Aerosol concentrations were measured with the Frontier Enterprise sodium flame photometer. Aerosols of beryllium sulfate, cadmium iodide, and lead nitrate were "spiked" with small quantities of sodium chloride so that their concentrations could be measured in the flame photometer. Samples for concentration measurement were extracted through two one-quarter inch diameter sampling lines which were of the same length. The flame photometer had an internal peristaltic sampling pump. A plate-type orifice flow meter was used to monitor the sample flow rate, which was maintained at two liters per minute by adjusting the peristaltic pump speed. For measurements on filters with high pressure drops, the peristaltic pump tubing tended to collapse, thus reducing the sample flow; the pump speed was, therefore, increased to overcome this. For some filters, the air resistance was so large that measurements were not possible with this system.

Initially, some work was done using an Environment One Model Rich 100 Condensation Nuclei Counter as a means of measuring particle concentration. This device was found to be less satisfactory than the flame photometer in that its internal sampling pump was not capable of pulling a sample from the downstream side of filters which exhibited a high pressure drop, i.e., it could not sample from low pressure sources. (This was a greater problem with the CN counter than with the flame photometer.) Also, there were some questions about the linearity of the instrument response.(31)

Aerosol particle samples were collected for size analysis by electron microscopy with a Walkenhorst-type thermal precipitator.[33,34] Particles were collected on carbon-coated mica substrates. The collected particles were shadowed with platinum and then over-coated with a second layer of carbon. This sandwich was floated off the mica by inserting the substrates edgewise into a dish of water. The carbon film floated on the water surface and was picked up on a copper electron microscope grid. After drying, the grids were examined with a Hitachi HU11 transmission electron microscope.

Photographs of a representative area of this particle deposit were taken for size analysis. A distribution of projected area particle diameter was obtained from the photographs with a Zeiss-Entler particle size analyzer. An approximate volume distribution was obtained by multiplying the diameter distributions by a factor relating diameter to volume. In some cases, the particles were cubical so the volume distribution was reasonably accurate; however, in other cases, the particles observed in the photographs were lens-shaped. This was probably due to adsorption of water vapor (some of the salts may have been hygroscopic) or possibly incomplete dehydration during aerosol generation. For these cases, the volume distribution is likely to be inaccurate. Also, in such cases, the relation between the particles observed on the microscope grids and those in the aerosol is uncertain, and the former must be regarded only as a rough "indicator" of the latter.

Initially, some attempt was made to collect particles on 0.03 micron Nuclepore filters for size analysis. This proved to be unsatisfactory due to difficulties in processing the samples. The procedure was as follows: Samples were collected on the filter. The filter was then shadowed with platinum and coated with carbon. The filter was dissolved with an organic solvent leaving the carbon film replica of the particle behind. Difficulties were encountered in dissolving the filter completely. Due to these problems, the thermal precipitator approach was adopted. Later it was discovered that these dissolution problems were associated with the filters of the particular batch used.

Initially, a series of experiments were conducted that involved generating aerosols with different concentrations of salt solutions and measuring the particle sizes produced to determine the relationship between salt solution concentration and particle size. After this relationship was established, efficiency measurements were carried out for these aerosols.

The linearity of the flame photometer was also evaluated. Sodium chloride aerosols of several concentrations were generated by nebulization of salt solutions of different concentrations. The aerosols were sampled simultaneously with a filter and by the flame photometer. The filter was subsequently analyzed for sodium content by atomic absorption spectrophotometry. This permitted comparison of the photometer reading with aerosol concentration. The results are given in Figure 12. The sodium concentrations used in the filter efficiency measurements were kept below the level where serious deviations from linearity commenced, corresponding to a concentration of $\sim 0.3\ mg/m^3$.

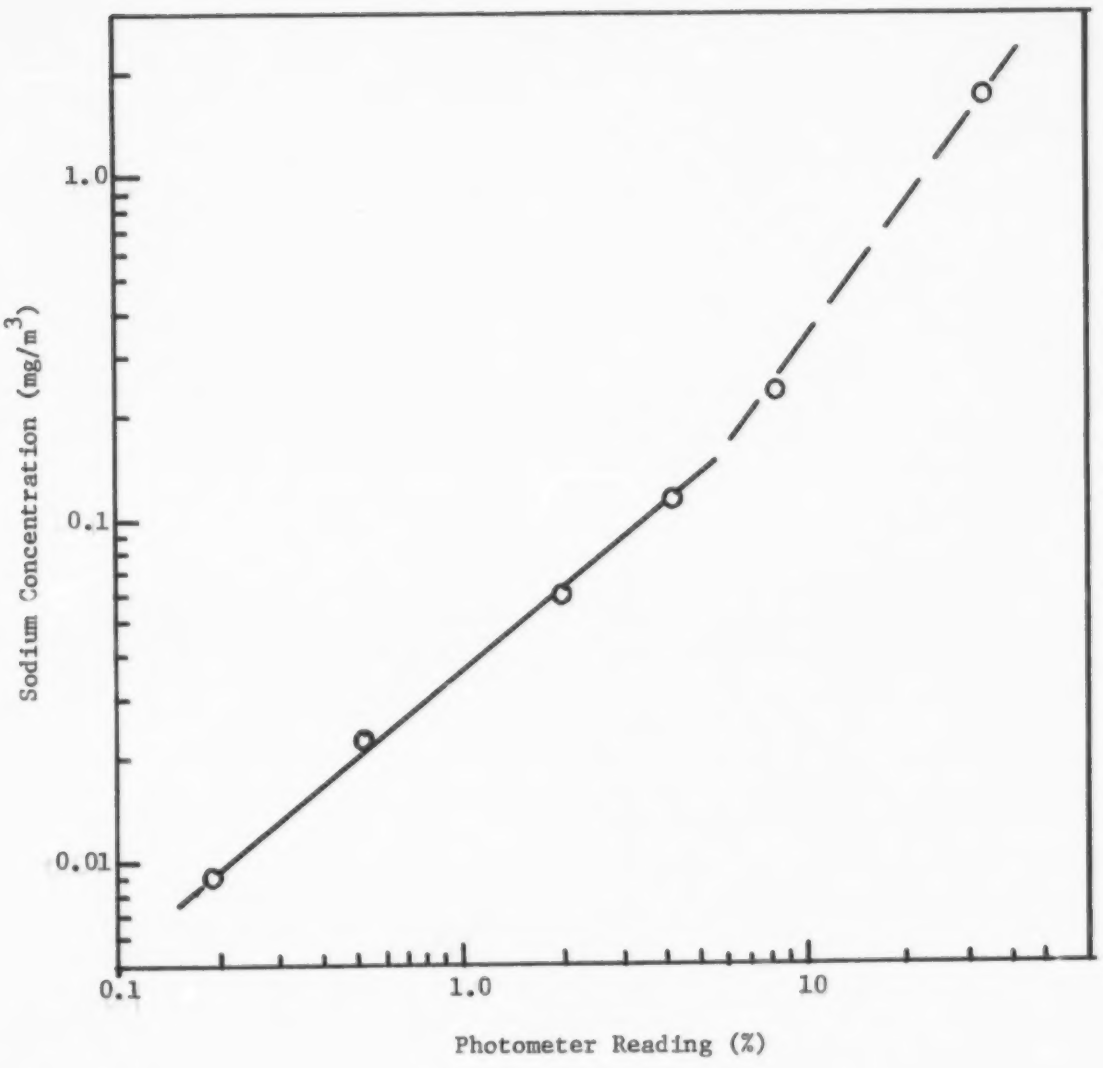


Figure 12. Calibration curve for Frontier Enterprises Flame Photometer.

A typical experimental run was conducted as follows. A salt solution of the appropriate concentration was prepared by dissolving an accurately weighed quantity of the salt in distilled water. The solution was placed in the nebulizer and the aerosol produced. After allowing several minutes for the system to stabilize, a filter was placed in the chuck and the aerosol flow through the filter adjusted to the appropriate value. Upstream and downstream concentrations were measured with the flame photometer and the air resistance recorded. The flow was adjusted to the second value and the concentration measurements repeated. Next, a plastic mask (14.2 cm^2 area) was placed over the filter to restrict flow through the filter to a smaller area. Efficiency measurements were made again at two aerosol flow rates. Finally, a second smaller mask (9.4 cm^2 area) was placed over the filter and a fifth efficiency measurement made. The measurements were then repeated on a fresh filter sample proceeding in the reverse order. The entire sequence was then repeated for other filter media.

Samples for particle size analysis were collected after refilling the nebulizer with fresh salt solution. In some cases, it was necessary to collect samples for particle size analysis on different days if satisfactory samples were not collected in the first attempt.

SECTION 8

RESULTS AND DISCUSSION

The measured 0.3 μm DOP efficiencies for three fiber and two membrane type filters are given in Table 3. Two important observations can be made from these data: 1) the efficiencies for all of the filters tested were very high - in excess of 99.9 percent, and 2) filter efficiency and air resistance can vary substantially from one filter lot to another. The variation in air resistance for the Fluoropore media is particularly large.

An efficiency of 99.9 percent is certainly adequate for the measurement of metal concentrations in an aerosol; in fact, an efficiency of 99 percent would be acceptable. The data of Table 3 do not necessarily imply that all particles would be collected with 99 percent + efficiency, as particles smaller than 0.3 microns may have higher penetrations. In cases where a significant fraction of the aerosol mass is associated with particles much smaller than 0.3 microns, an underestimate of the true concentration could result. In order to assess the likelihood of this possibility, measurements were also made of efficiency for smaller particles.

Electron micrographs of the various metallic salt aerosols are presented in Figures 13 to 15. The median particle size and geometric standard deviation (determined from measurements of at least 500 particles) are given in Table 4, which also lists the concentrations of the solutions from which the aerosols were generated. On the basis of particle shape and height, determined from the electron micrographs, a correction factor (R) was determined relating the particle projected area (A) and height (h) to the equivalent spherical diameter (d), as follows:

$$R \times f\ (A,h) = \frac{\pi}{6} d^3 \text{ or } d = \left[\frac{6\ R \times f\ (A,h)}{\pi}\right]^{\frac{1}{3}} \qquad (5)$$

R values and the calculated mass median diameters for each of the salts is also given in Table 4.

Aerosol size distributions for the various samples are shown in Figures 16 to 18. The distributions are of the log normal type except for the high concentration NaCl, ERC generator, and the high concentration $Pb(NO_3)$, DeVilbiss generator, which are bimodal. For these cases, the geometric standard deviation is not a good indicator of the width of the size distribution. A second measurement of this particular NaCl aerosol yielded almost identical results. It is concluded that the bimodal distribution is a result of the particular generation conditions and is not an artifact.

Measured efficiencies for the various salt aerosols are presented in Tables 5 to 8. With the exception of the Millipore Mitex and Whatman 41 filters, for which aerosol exposures were limited to the three sizes of NaCl, all filters exhibited efficiencies of greater than 99 percent for the entire set of salt compositions, particle sizes and flow rates evaluated. Values of air resistance for the various test conditions are given in Table 9.

TABLE 3. DIOCTYL PHTHALATE (DOP) EFFICIENCIES
(0.3 μm Particle Size at 5.3 cm/sec)

Filter Type	Lot	Efficiency (%)	Air Resistance (mm Hg)
MSA 1106 BH	JA4212	99.99	2.4
	J5822	>99.99	3.5
	J9350	99.99	2.9
ADL/Balston Microquartz	*	99.988-99.996	3.5-3.7
Gelman Spectro Grade (without silicone)	*	>99.99	3.0-3.5
Millipore Fluoropore FA (1 μm pore size)	06927	>99.99	10.1
	09693	99.998	5.5-5.7
	35348	99.998	7.7
	37041	99.999	7.7-8.1
Millipore AA (0.8 μm pore size)	352072	99.997	14.7
	357302	99.998	16.1
	37356-12	99.999	14.1-14.2

*Experimental filters, with only one trial lot available

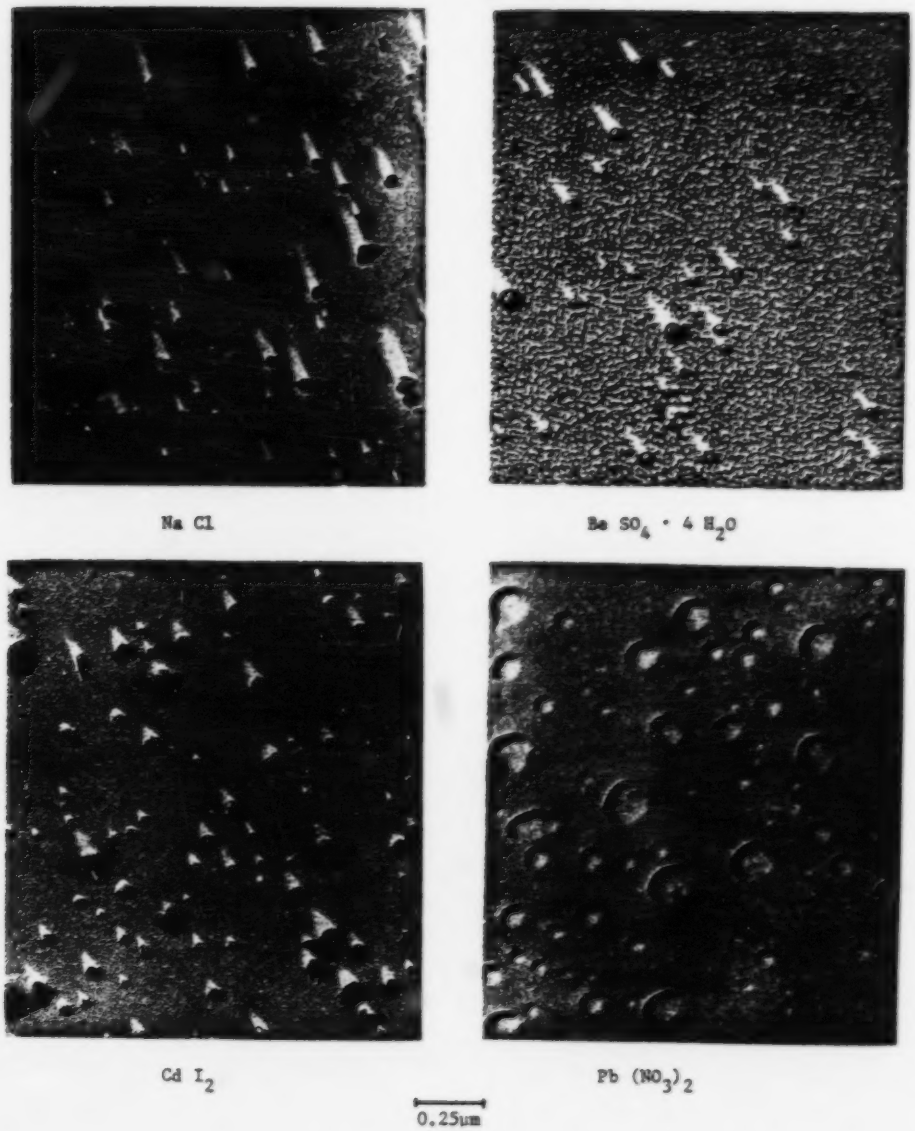


Figure 13. Electron micrographs of metallic salt particles representing smaller size from ERC Generator (41,500X).

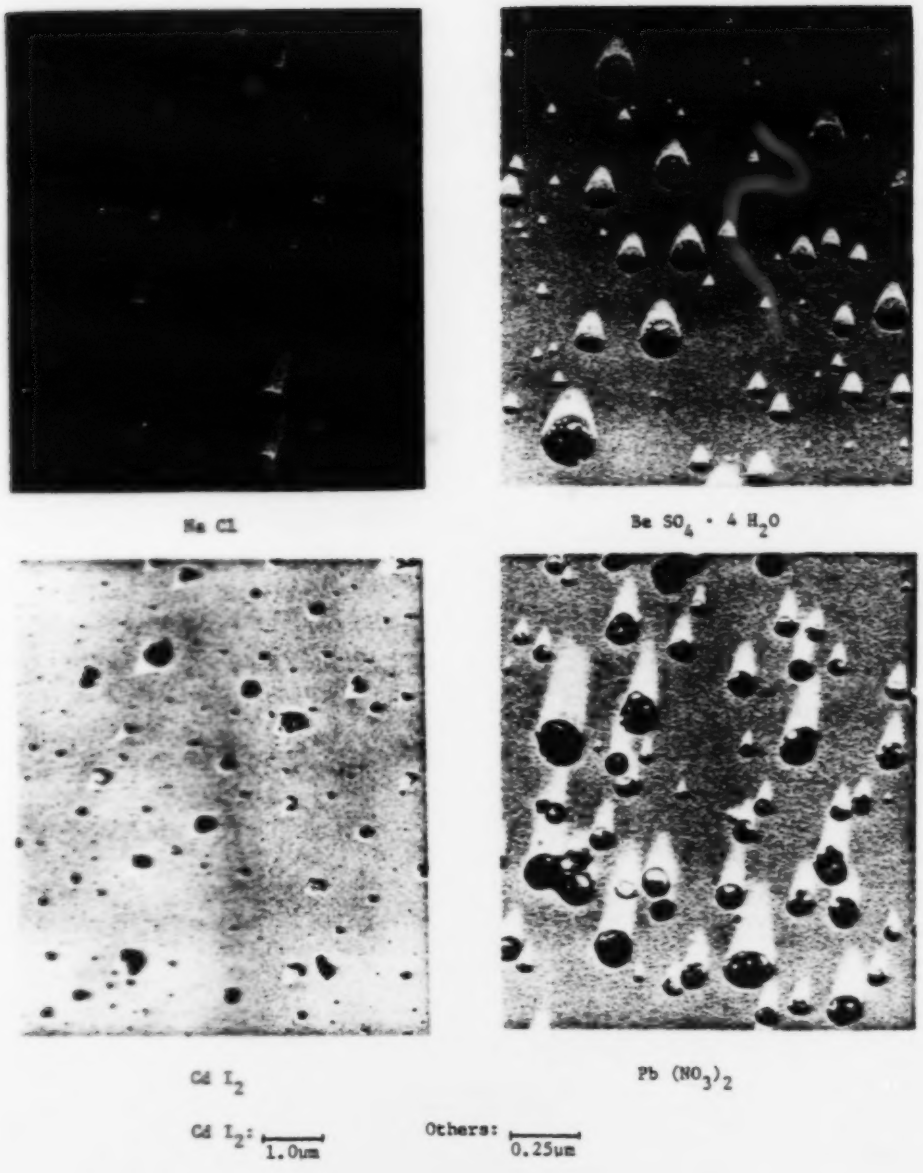


Figure 14. Electron micrographs of metallic salt particles representing larger size from ERC Generator (Cd I_2-12,500X); others-41,500X).

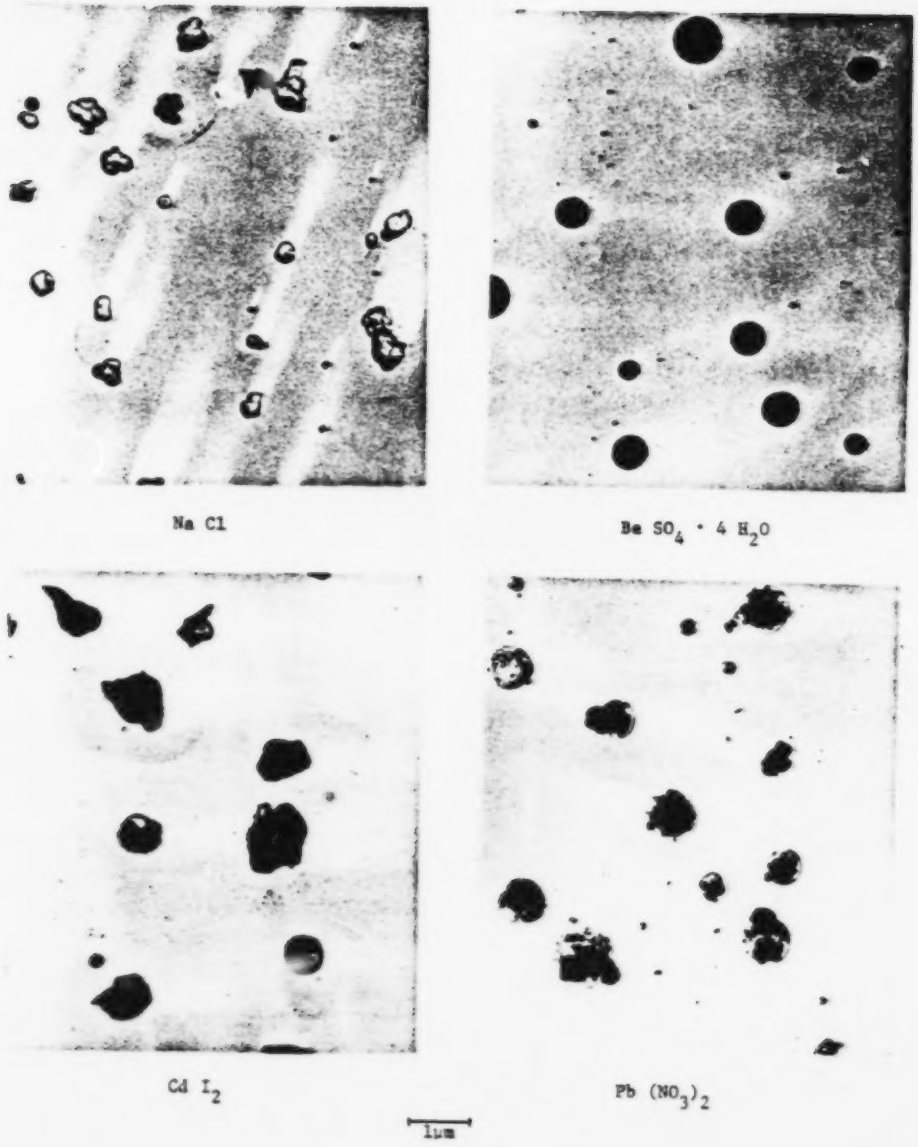


Figure 15. Electron micrographs of metallic salt particles from DeVilbiss Generator (12,500X).

TABLE 4. SALT AEROSOL PARTICLE SIZE

Salt	Solution Conc - g/ℓ (NaCl + Salt)	Generator	Number Median Diameter (μm)	Geometric Standard Deviation	R Factor	Mass Median Diameter (μm)
NaCl	0.5	ERC	0.018	1.48	0.37	0.031
	5	ERC	0.028	1.84	0.37	0.063
	5	DeVilbiss	0.15	1.85	0.37	0.30
$BeSO_4 \cdot 4\ H_2O$	0.1 + 0.39	ERC	0.034	1.35	1.0	0.052
	0.5 + 3.9	ERC	0.056	1.63	0.25	0.098
	0.5 + 3.9	DeVilbiss	0.83	1.94	1.0	1.31
CdI_2	0.1 + 1.36	ERC	0.039	1.30	0.32	0.045
	1 + 13.6	ERC	0.092	1.49	0.37	0.135
	1 + 13.6	DeVilbiss	0.403	1.54	0.37	0.498
$Pb\ (NO_3)_2$	0.1 + 1.04	ERC	0.070	1.39	0.5	0.098
	1 + 10.4	ERC	0.066	1.58	0.5	0.108
	1 + 10.4	DeVilbiss	0.305	1.89	0.5	0.586

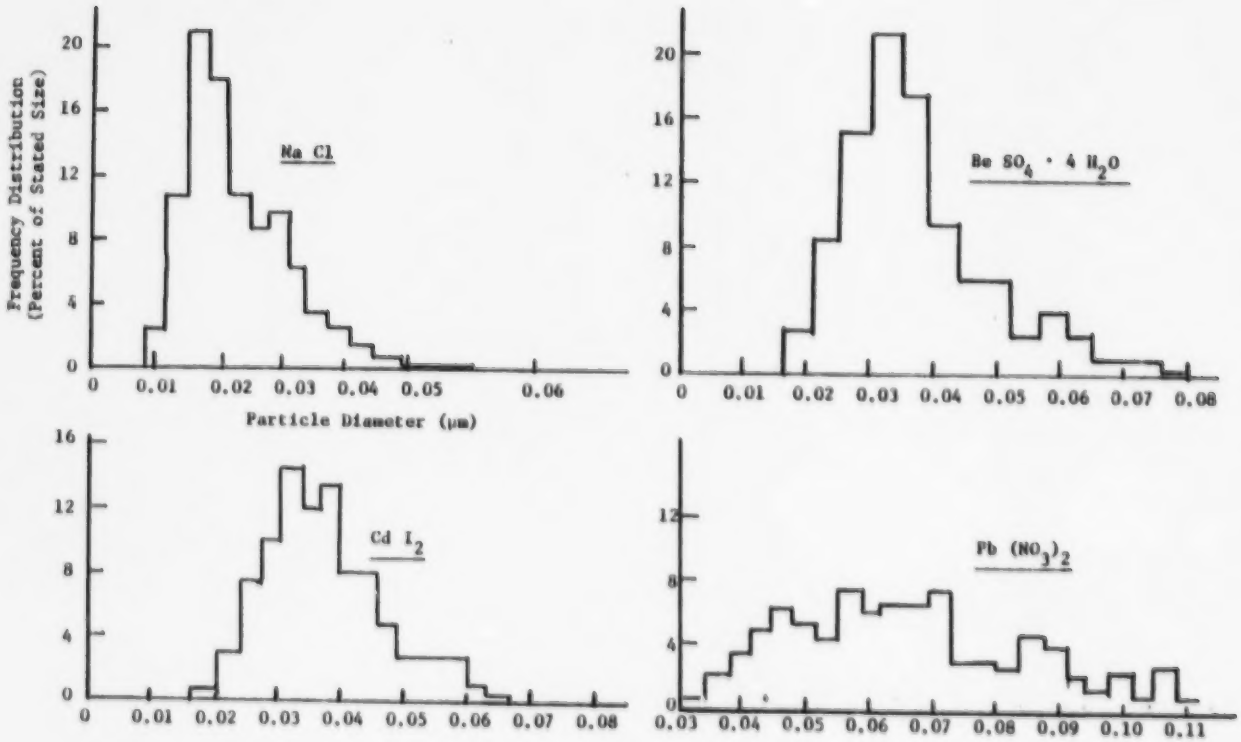


Figure 16. Frequency distribution by size for smaller aerosols from ERC Generator.

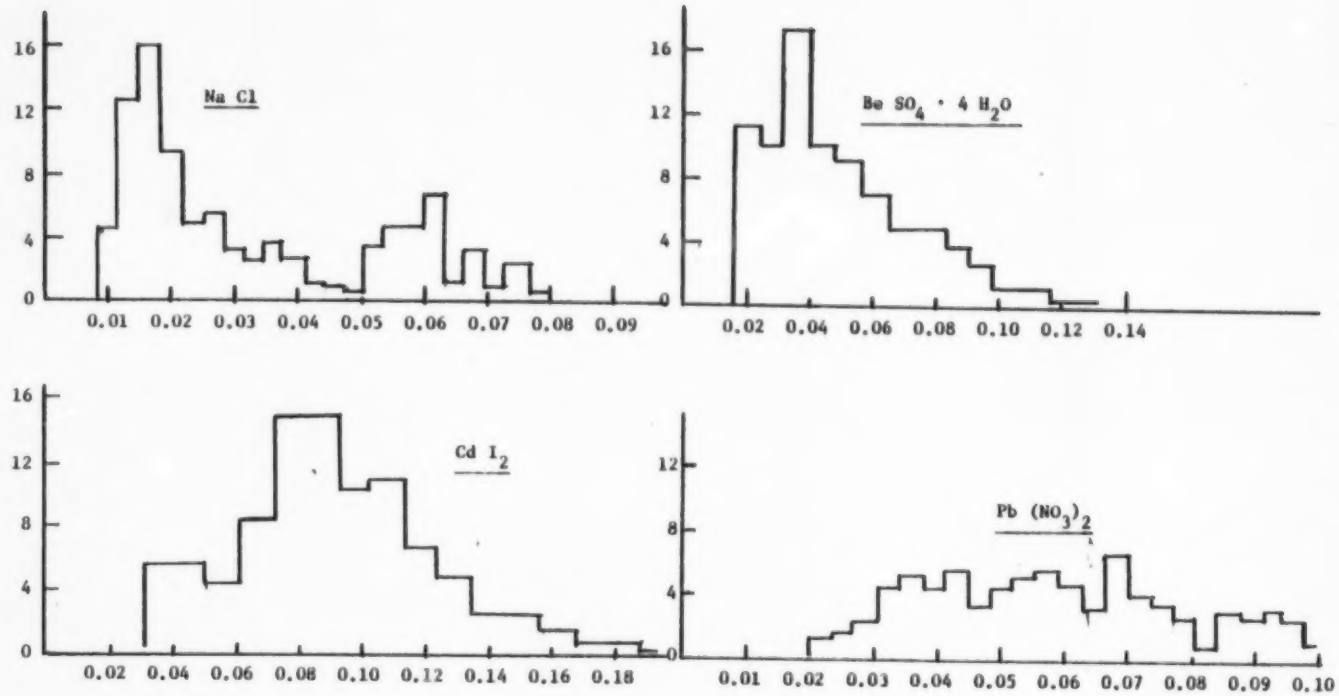


Figure 17. Frequency distribution by size for larger aerosols from ERC Generator.

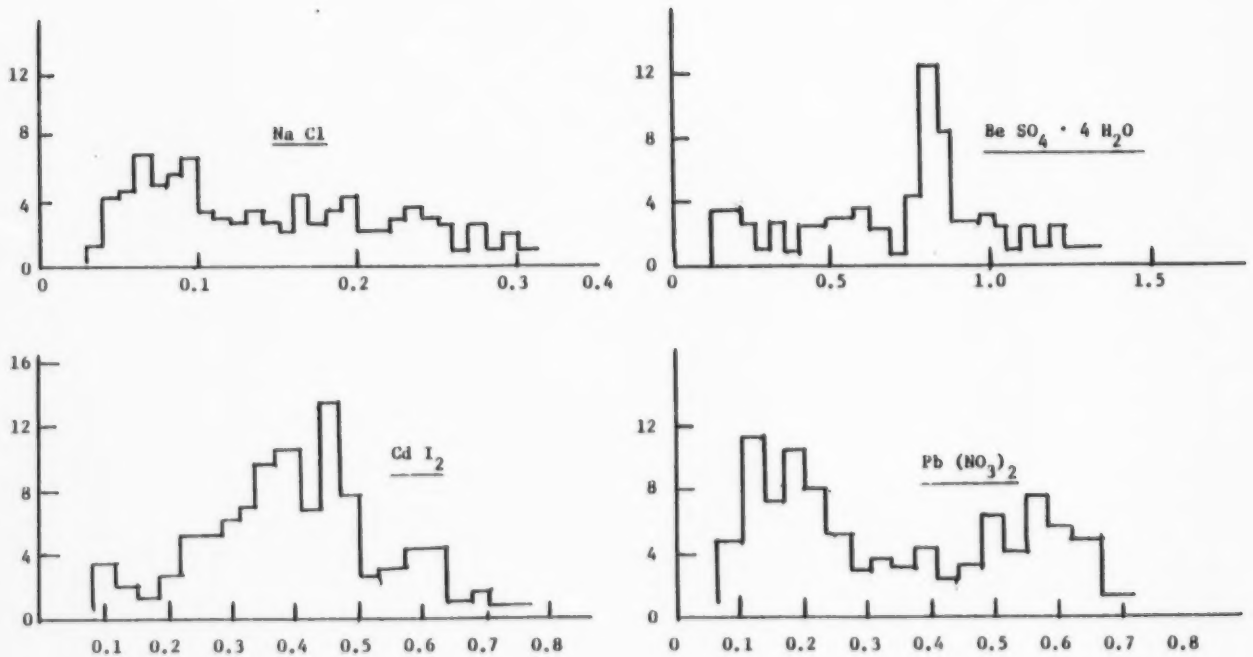


Figure 18. Frequency distribution by size for aerosols from DeVilbiss Generator.

TABLE 5. FILTER EFFICIENCIES FOR SODIUM CHLORIDE AEROSOLS

Filter Media	Face Velocity (cm/sec)	Efficiency for Individual Particle Size (%) 0.03 (μm)	0.06 (μm)	0.3 (μm)
MSA1106BH	4	99.9	>99.9	>99.99
	12	99.9	>99.9	>99.99
	30	99.9	99.8	>99.99
	83	99.3	99.8	>99.99
	126	99.3	99.6	>99.99
ADL Microquartz	4	99.9	>99.9	>99.99
	12	99.9	>99.9	>99.99
	30	99.8	99.8	>99.99
	83	99.2	99.7	>99.99
	126	99.1	99.4	>99.99
Gelman Spectro Grade (without silicone)	42	99.9	>99.9	>99.99
	12	99.9	>99.9	>99.99
	30	99.8	99.9	>99.99
	83	99.3	99.2	>99.99
	126	99.2	99.5	>99.99
Fluoropore FA	4	>99.9	>99.9	>99.99
	12	>99.9	>99.9	>99.99
	30	>99.9	>99.9	>99.99
	83	99.8	>99.9	>99.99
Millipore AA	4	>99.9	>99.99	>99.99
	12	>99.9	>99.99	>99.99
	30	>99.9	>99.99	>99.99
MITEX (10 micron pore size)	4	76	—	—
	12	71	—	—
	30	74	—	—
Whatman 41	4	51	—	—
	12	53	—	—
	30	45	—	—
	83	55	—	—

TABLE 6. FILTER EFFICIENCIES FOR BERYLLIUM SULFATE AEROSOLS

Filter Media	Face Velocity (cm/sec)	Efficiency for Individual Particle Size (%) 0.05 (μm)	0.19 (μm)	1.3 (μm)
MSA1106BH	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	99.9	>99.9
	83	>99	99.7	>99.9
	126	>99	99.6	>99.9
ADL Microquartz	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	99.8	>99.9
	83	>99	99.5	>99.9
	126	>99	99.4	>99.9
Gelman Spectro Grade (without silicone)	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	99.8	>99.9
	83	>99	99.4	>99.9
	126	>99	99.7	>99.9
Fluoropore FA	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	>99.9	>99.9
	83	>99	>99.9	>99.9
Millipore AA	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	>99.9	>99.9

TABLE 7. FILTER EFFICIENCIES FOR CADMIUM IODIDE AEROSOLS

Filter Media	Face Velocity (cm/sec)	Efficiency for Individual Particle Size (%) 0.05 (μm)	0.15 (μm)	0.5 (μm)
MSA1106BH	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	>99.9	>99.9
	83	>99	>99.9	>99.9
	126	>99	>99.9	>99.9
ADL Microquartz	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	99.8	>99.9
	83	>99	99.8	>99.9
	126	>99	99.8	>99.9
Gelman Spectro Grade (without silicone)	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	>99.9	>99.9
	83	>99	>99.9	>99.9
	126	>99	>99.9	>99.9
Fluoropore FA	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	>99.9	>99.9
	83	>99	>99.9	>99.9
Millipore AA	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	>99.9	>99.9

TABLE 8. FILTER EFFICIENCIES FOR LEAD NITRATE AEROSOLS

Filter Media	Face Velocity (cm/sec)	Efficiency for Individual Particle Size (%) 0.10 (μm)	0.11 (μm)	0.6 (μm)
MSA1106BH	4	>99	>99.9	>99.9
	12	>99	99.9	>99.9
	30	>99	99.8	>99.9
	83	>99	99.7	>99.9
	126	>99	99.6	>99.9
ADL Microquartz	4	>99	>99.9	>99.9
	12	>99	99.9	>99.9
	30	>99	99.8	>99.9
	83	>99	99.8	>99.9
	126	>99	99.8	>99.9
Gelman Spectro Grade (without silicone)	4	>99	>99.9	>99.9
	12	>99	99.9	>99.9
	30	>99	99.9	>99.9
	83	>99	99.8	>99.9
	126	>99	99.8	>99.9
Fluoropore FA	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	>99.9	>99.9
	83	>99	>99.9	>99.9
Millipore AA	4	>99	>99.9	>99.9
	12	>99	>99.9	>99.9
	30	>99	>99.9	>99.9

TABLE 9. AIR RESISTANCE OF FILTER MEDIA

Media	Face Velocity (cm/sec)	Pressure Drop (mm Hg)
MSA1106BH	4	2.1
	12	6.2
	30	14.0
	83	42.7
	126	62.5
ADL Microquartz	4	2.7
	12	6.6
	30	16.0
	83	47.8
	126	72.1
Gelman Spectro Grade (without silicone)	4	2.1
	12	6.2
	30	15.1
	83	44.1
	126	63.0
Fluoropore FA	4	4.5
	12	13.8
	30	38.0
	83	114.0
Millipore AA	4	11.5
	12	31.7
	30	78.0
Whatman 41	4	1.5
	12	4.4
	30	12.4
	83	41.9
MITEX (10 micron pore size)	4	5.2
	12	16.0
	30	41.2

In some instances, the actual efficiencies were greater than could be measured by the experimental technique employed. This was due to the fact that the NaCl portion of the aerosol on the downstream side of the filter was too low in concentration to be distinguished from background noise in the sodium flame photometer.

The Millipore AA and Fluoropore membrane filters were observed to have the highest efficiencies; however, the air resistance of these filters was also very high, as is shown by Table 9. At the higher test velocities, it was not possible to measure the efficiency of these filters as the sodium flame photometer sampling pump was unable to extract samples from the downstream side of the filter due to the high air resistance.

In general, efficiencies are observed to decrease slightly with increasing velocity. This behavior is expected as the very small aerosol particles are collected, for the most part, by the diffusion mechanism. Because of the limited dynamic range of the sodium flame photometer together with the high efficiency of these filters, it was not possible to observe any effects that can be related to the differing densities of the test aerosols.

The results of this study compare favorably with other studies conducted on the same or similar filters, as follows:

- Sinclair[34] found that the efficiency of MSA 1106B (similar to 1106BH, except that it has an organic binder) has efficiencies of the same magnitude as observed for MSA 1106BH in this study.

- Lundgren and Gunderson[35] report very similar collection efficiencies for Arthur D. Little/Balston Microquartz, MSA 1106BH and Gelman Spectrograde (and also Gelman A and Gelman E) filters for particle sizes of 0.05 to 6.0 μm MMD and flow velocities of 5 to 50 cm/sec. For equivalent experimental conditions, their results agreed well with the findings of this study.

- Liu and Lee[36] observed efficiencies of greater than 99.99 percent for Millipore and Fluoropore filters (0.5 μm pore size) for particle sizes of 0.03 to 1.0 μm, comparable to the results reported here.

SECTION 9

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